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WOOD AND OTHER RENEWABLE RESOURCES • CASE STUDY

Life cycle assessment comparison among different reuse intensities for industrial wooden containers

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Abstract
Goal, scope and background The industrial packages sector has great importance for the transport sector in Europe. These containers, mainly wooden pallets and spools, are subject to European legislation, which promotes their reuse and recycling. This study uses life cycle assessment (LCA) to assess the environmental impact of the current management system in this sector and the benefits and drawbacks of different reuse intensities as a waste prevention strategy as opposed to the recycling option.
Materials and methods In this paper, four case studies located in Spain and representative of the wooden package sector in Europe are analysed: high reuse pallet, low reuse pallet, low reuse spool and null reuse spool. For the LCA study cases, the functional unit is that required to satisfy the transport necessity of 1,000 t by road. The impact and energy consumption assessment methods used are CML 2 Baseline 2000 and Cumulative Energy Demand. Data are mostly provided by the leading enterprises and organisations in this sector.
Results The paper provides, as a first result, a comprehensive inventory of the systems under study. Secondly, our assessment shows that the systems with higher reuse intensity show a reduction in energy and wood consumption and all the environmental impact categories except for the global warming potential from 34.0% to 81.0% in the pallet study cases and from 50.4% to 72.8% in the spool ones. This reduction is at the expense of the maintenance stage, which on the contrary increases its impact, although it is still relatively small—less than 7% in all the impact categories and flow indicators of the study cases. The highest impact stages are transport, raw material extraction and the process chain. The final disposal and maintenance stages are the lowest impact, contributing at most to less than 30% of the impact in the pallet study cases and 10% in the spool cases.
Discussion Wood consumption (WC), directly related to the number of containers needed to satisfy the functional unit, is the main factor in determining the impact of the stages, especially in the raw materials extraction and process chain stages, assuming that these are undertaken with the same technologies in all the case studies. Other variables, such as the management system, the maintenance index and the final disposal scenario, affect the impact of the remaining stages: transport, maintenance and final disposal. The global warming potential results obtained demonstrate the environmental benefits of using containers made of a renewable resource such as wood instead of using other materials, but these results are not expected to prioritise the lower reuse systems because of their better performance in this category.
Conclusions Reuse, a strategy capable of reducing the environmental impacts of the wooden container systems, is preferable to recycling, while the package maintenance tasks are still feasible. Therefore, reuse, combined with recycling as final disposal, should be encouraged to reduce the demand for natural resources and the waste generated.
Recommendations Based on these results, attention should be paid to the maintenance stage, which, being the lowest-impact one, could substantially reduce the impact of the remaining stages.

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1 Introduction

The industrial packages area has been growing enormously since the 1960s in Europe (Hischier et al. 2005). Transport is an expanding sector of the economy that accounts for some 1,000 billion € or more than 10% of the European Union's gross domestic product and employs 10 million people (European Commission 2001) being the main consumer of containers such as pallets and spools. These sectors provoke an annual trade of about 350 million pallets, lightweight containers and industrial containers in the whole Europe, which represents about 20 million cubic meters of timber (European Federation of Wooden Pallet and Packaging Manufacturers 2006; European Confederation of Woodworking Industries 2006). These containers, mainly pallets and spools, are commonly made of wood, which is one of the raw materials often used for containers and is the world's most important renewable material and regenerative fuel (Hischier et al. 2005; Bowyer 1995; Eldag 1980; Schulz 1993; Sutton 1993). Furthermore, when wood is used as a raw material in the containers sector, it shows several environmental advantages compared with other materials such as plastic. In this direction, some life cycle assessments (LCAs) have been carried out to demonstrate that timber is an environmentally superior material to the other alternatives, as Hillier and Murphy (2000) have stated. Among these, we can highlight its capacity to act as a CO_2 sink during the first stage of its life cycle (Gustavson et al. 2006; IPCC 2001, Turkendburg et al. 2000) and the option of biomass cascading; this is to say, wood is first used for a material application, and next, it may be recycled for several further material applications, and finally, energy is recovered from the biomass (Dornburg and Faaij 2005).

Due to the fact that packaging material has already fulfilled its function at the beginning of the use phase of the respective product and is then turned into waste, the environmental relevance of containers materials became very important (Hischier et al. 2005). In this sense, the Directive 2004/12/EC of the European Parliament and of the Council of 11 February 2004 amending Directive 94/62/EC on packaging and packaging waste (EU 2004) promotes a better environmental management of container waste by means of its recovery or incineration with energy recovery. Special emphasis is made to package waste recycling, which is a favourable environmental option as has been demonstrated by Rivela et al. (2006a), Arena et al. (2003) and Mata and Costa (2001) for the wood, plastic and glass container sectors, respectively. However, in line with the previous community strategy for waste management set out in Council resolution of 7 May 1990 on waste policy and Council Directive 75/442/EEC of 15 July 1975 on waste, the management of containers and containers waste should include as a first priority the prevention of container waste and, as additional fundamental principles, reuse of containers, recycling and other forms of recovering container waste and, hence, a reduction in the final disposal of such waste (EU 1994). This article is mainly centred on the assessment of the reuse intensity of the containers and their environmental effects on the package life cycle to eventually decide which is better: reuse or recycling.

Assuming all these sets of facts, it has been considered that some case studies are necessary to obtain empirical data representative of the real situation throughout the developed countries to show the effects of wooden container reuse in systems that assume recycling as their main final disposal option. This study analyses four wooden package systems in Spain as they provide a good source of data from the leading associations and representatives of the country's wood sector: the leading Spanish association of cable, electric conductor and fibre optics manufactures (FACEL) and the leading global European enterprise in pallet and container pooling services (CHEP). LCA methodology has been applied to the two main wooden containers, pallets and spools, which represent more than 80% in mass of the total amount of wooden containers in Spain (INE 2006a) and have also become widespread in most countries. Most of the conclusions that are drawn in this study can be extended to other European countries, as these containers have similar characteristics abroad and the transport logistics are comparable due to the fact that goods transport is mainly by road in Spain as in EU-25 (INE 2006b). Based on the results of the LCA, this study found some interesting implications for the target audience namely, the wood containers industry.

2 Goal and scope

2.1 Objectives

The objectives of this study were to develop a life cycle inventory analysis and to analyse the environmental impacts of the current management system by means of a life cycle inventory assessment. We also aimed to draw out the benefits and drawbacks derived from the reuse of wood containers and to see the extent to which reuse intensity affects them to demonstrate that reuse is preferable to recycling. In addition to that, several other specific aims are to identify the highest impact stages of the life cycle and the variables that condition them.

2.2 Functional unit

This unit provides a reference for the inputs and outputs (ISO 2006; Lindfors et al. 1995). Two functional units were chosen, one for each typology of wooden container under study: pallets and spools.

The functional unit chosen for the pallet systems was to satisfy the transport necessity for 1,000 t by road of a product whose density is 1 t/m^3 with wooden pallets in Spain.

The functional unit chosen for the spools systems was to satisfy the transport necessity for 1,000 t by road of electrical cable or optics fibre with wooden spools in Spain.

In these case studies, the extraction of raw materials, production, transport, use, maintenance (in the case that it existed) and the final disposal of the waste were taken into account, in a 'cradle to grave' approach.

2.3 Description of the system under study

The case studies comprise two container typologies and four scenarios namely: high-reuse pallet (HR Pallet), low-reuse pallet (LR Pallet), low-reuse spool (LR Spool) and null-reuse spool (NR Spool). Whereas the pallet case studies show a real example of high- and low-reuse intensities (HR Pallet and LR Pallet), the spool cases illustrate one of low or null (LR Spool and NR Spool), so they allow us to compare different reuse intensities based on empirical data from 2005.

Pallets and spools are made mainly of pinewood and, to a lesser extent, with steel nails, paint and other materials. The dimensions of the pallets are due to international logistics standards (EUR-pallet), whereas a huge variety of spools are manufactured according to the specifications required by consumers. The typical sizes of the pallets are 1,200×800 mm (length×width), and the spools are 1,200×800 mm (exterior diameter×cylinder height), as stated by the main producers in the country. The characteristic pallet weight is 25 kg, and the spool weight is 85 kg. All the flows and inventory data refer to the characteristics shown in Table 1.

Each pallet and spool factory has its own process conditions; however, the general flow sheet is common in all of them. The main stages of the wooden container sectors analysed are: raw materials extraction, process chain, use, maintenance and final disposal. Auxiliary stages that must be computed throughout all the processes are the transport activities involved. The description of the system evaluated is presented in Fig. 1.

1. Raw Materials Extraction (RME). The main raw material is timber from the national forestry from the varieties *Pinus pinaster* and *Pinus sylvestris* because of its economic and technical advantages, its highly competitive price in the Spanish market and its appropriate physical characteristics (Confemadera 2006).

The processes included in obtaining it are tree felling, log debarking, natural drying at the sawmill and the land use accounted for. The trees deforested are substituted by new trees that involve absorption of carbon dioxide from the atmosphere during photosynthesis in plantations. This CO_2 sequestration amounts to 897 kg CO_2 per each cubic meter of softwood, standing under bark in forest (Werner et al. 2003).

Wood wastes from this stage are destined to composting as a sub-product, so their environmental impacts are allocated to this process. When assessing the environmental impacts of this stage, only the materials extracted for the process chain are accounted for, assigning the impacts left to the maintenance stage.

Other relevant raw materials are low-alloy steel nails and the alkyd paint in solvent, produced from a specific long-oil alkyd.

2. Process chain. The process chain can be subdivided into two main sub-systems. The material input is refined, classified and dried (subsystem of wood preparation and board shaping) and then put together with the nails and other secondary materials and sanded into the final product (subsystem of product assembly).

   2.1 Subsystem of wood preparation and board shaping. The dried debarked logs are first sawn into vast planks, which are then sawn into specific dimensions to obtain wooden boards, blocks, axles and disks. Lumber processing residues consist of edging, slabs, shavings, trimmings,

Table 1 Case-studies basic characteristics provided by the leading associations and representatives of Spain's wood sector (FACEL 2006; CHEP 2005)

	Life time (years)	Number of uses/life time	Capacity (t/unit)	Percent of containers that require maintenance	Number of wood containers per FU
HR Pallet	10.0	30.00	1.00	23	33
LR Pallet	2.0	4.40	1.00	8	227
LR Spool	2.3	3.57	1.25	25	224
NR Spool	0.4	1.00	1.25	0	800

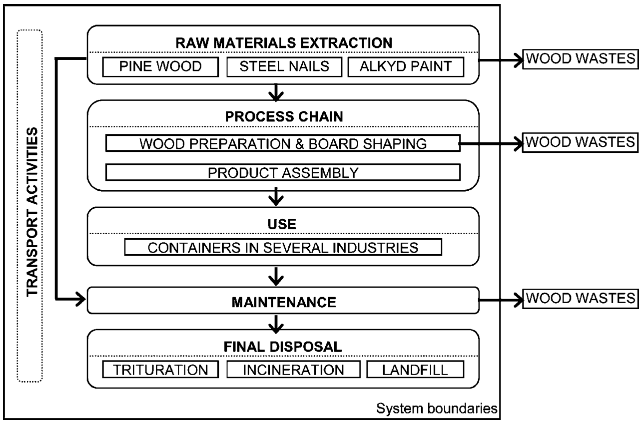

Fig. 1 System boundaries and process chain under study

sawdust and pieces of wood, which are sent as sub-products to other processes.

2.2 Subsystem of product assembly. Wooden boards, blocks, axles and disks, whose dimensions are re-adjusted according to the desired pallet or spool size, are painted according to the company's corporative image and are eventually manually assembled with the steel nails using pneumatic hammers. Other complementary materials, such as glues, cramps or wires, are commonly used to strengthen the container structure and reinforce its resistance. However, they are not taken into account in this system because of the low consumption per unit of wood container produced, as stated by the producers.

3. Use. Wooden pallets are mainly used in the transport sector and its related industries: automotive, beverage, raw material/containers, petro-chemical, grocery, home improvement/do-it-yourself and fresh fruit and vegetable. Wooden spools are used to package electrical and fibre optic conductors and cables. The number of uses of the wooden containers varies greatly along the four study cases as does their lifespan (see Table 1).
4. Maintenance. Pallets and spools are subject to inspection after use to decide if they can be directly reused, whether they need maintenance processes or if they are considered waste because of their bad condition. Maintenance is only carried out manually on those containers easily reparable (see Table 1—percent of containers that require maintenance) and consists of nail and nut re-adjustment, board substitution or both. This stage is not incorporated in the null reuse spool management system (NR Spool). When assessing the environmental impacts, this stage also includes the extraction of raw materials to carry out the maintenance tasks.
5. Final disposal. There are three main possibilities of final disposal: (a) recycling by wood grinding and particle-board manufacture, (b) energy recovery by means of incineration or (c) disposal to a landfill. According to the Spanish wooden container sector, the most common case is the recycling option (100%), as occurs with HR pallets and also all types of spools. This alternative decreases the demand for virgin fibre and reduces the quantity of used packaging going to the landfill (Ross et al. 2003). However, the final disposal of LR Pallets presents all the possibilities mentioned before: recycling (85%), incineration (9%) and landfill (6%), as stated by its stakeholders.
6. Transport activities. The activities involved in this stage include all transport between the various agents that make up the system (Fig. 2).

2.4 Data quality

The pallet case studies data (HR Pallet and LR Pallet) was provided by CHEP, which is the global European leading enterprise in pallet and container pooling services, serving customers in a wide range of industrial and retail supply chains.

The spools case study data (LR Spool and NR Spool) was provided by FACEL, the leading Spanish association of cable, electric conductors and fibre optic manufactures.

All the data related to the system agents' locations was provided by CHEP, FACEL and most of the wood containers manufacturers by means of an interview and also the Spanish Wood Recovery Association (ASERMA) and the Spanish Environmental Ministry (ASERMA 2006; Spanish Environmental Ministry 2006).

The input and output data for generalized and standard production processes such as the obtaining of the paint and the steel nails, the extraction and treatment of the wood as well as the data related to the life cycle of the fuel and electricity (production, distribution and consumption) were taken from ecoinvent Database (ecoinvent 2006).

The infrastructure of the wooden container production facilities was not taken into account as it has been assumed that its contribution to the overall impact is negligible (Werner et al. 1997).

2.5 Methodology

LCA is now becoming accepted as the most effective environmental tool to carry out a comparison of relative environmental burdens between different productive systems, as has been demonstrated in the wood sector (Rivela et al. 2006b). The LCA methodology permits the assessment of all environmental impacts associated with a product, process or activity by accounting and evaluating resource consumption and emissions (ISO 2006). The main challenges in applying it are the quality of inventory data and the subjectivity involved in the impact assessment methodology.

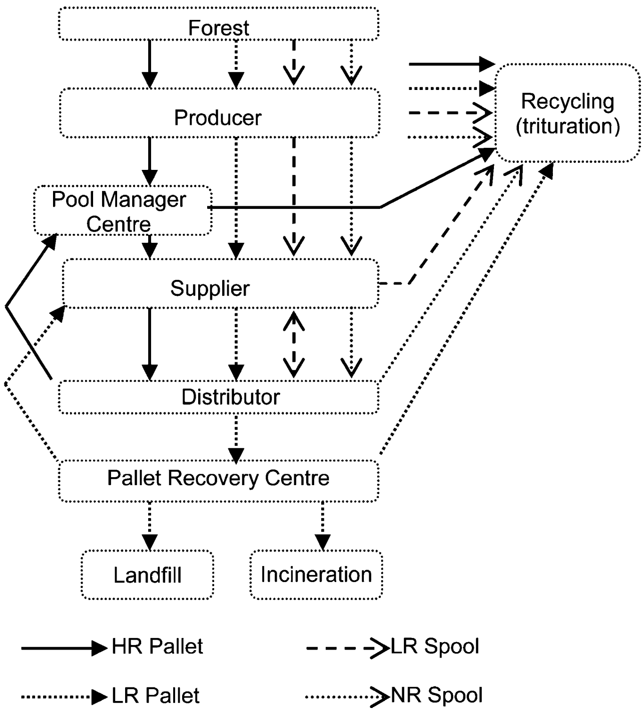

Fig. 2 Transport activities scheme in all the systems

Transport activities distances The average distances not available from the wooden sector sources have been calculated with a transport model, which takes into account a total of 80 different real routes, based upon the four following criteria: (1) the agents from each administrative region are located gathered in the industrial heart, (2) the routes considered cover the shortest distances, (3) the number of journeys is proportional to the number of agents in each capital centre and (4) all the agents have the same relative weight in terms of its contribution to the total number of journeys.

Impact assessment and energy assessment LCA methodology based on CML Leiden 2000 was used in this study to avoid subjectivity (Guinée et al. 2001). The midpoint impact categories considered have been: abiotic resources depletion (ARD), global warming potential (GWP), ozone depletion potential (ODP), human toxicity potential (HTP), acidification potential (AP) and eutrophication potential (EP). The software used in the environmental analysis was SimaPro 7.0., by Pré Consultants, as an LCA assistant tool and Excel, by Microsoft, as a data assistant tool.

Energy input assessment was carried out, using cumulative energy demand (Boustead and Hancock 2003; Pimentel 2003) to calculate the total direct and indirect amount of energy consumed (EC) throughout the life cycle of wooden containers in Megajoules per functional unit.

Flow indicators The WC indicator, conceived as an indicator of forest exploitation, is measured in tons of softwood standing trees per functional unit, and it has been calculated by means of the system described above (see Fig. 1).

3 Results

According to the systems defined by the functional unit, the results obtained are not comparable in absolute values between pallet and spool systems, but they are within each container system. Therefore, the results are presented comparing the pallet systems, on the one hand, and spool systems on the other.

3.1 Inventory data

The inventory data of all the systems is shown in Table 2.

According to the transport methodology described, the transport distances considered are shown in Table 3.

3.2 Life cycle inventory assessment

The systems with lower-reuse intensity (LR Pallet and NR Spool) show worse performance with regard to energy and WC. They have a greater demand in comparison to higher-reuse systems (HR Pallet and LR Spool) with a factor of 3 and 3.6 in energy terms and 5.3 and 3.6 in WC terms, respectively (Table 4).

Higher reuse systems show an impact reduction from 34.4% to 54.4%—pallet study cases—and from 50.4% to 66.3%—spool study cases—in all the impact categories except for GWP. This impact category shows a different pattern due to the wood-consuming stages namely, raw material extraction and maintenance, which reduce or even reverse the impact in this category despite the better performance of the remaining stages—process chain, transport and final disposal—in higher-reuse systems. The overall GWP impact category is positive in all the study cases except for HR Pallet, in which it is nearly negligible.

3.2.1 Stage-relative contribution to the environmental impact

Referring to the contribution of the different stages in each system on global impact, the results obtained show that the highest-impact stages are added transports, process chain and raw materials extraction, depending on the system evaluated (Tables 5, 6).

With regards to the pallet case studies (HR Pallet and LR Pallet, see Table 5, and Fig. 3), the highest-impact stage is transport, whose impact is approximately 1.2 times higher

Table 2 Inventory for functional unit

			HR Pallet	LR Pallet	LR Spool	NR Spool	ecoinvent process selected
RME	I	Softwood standing trees (t)	2.62	13.90	50.28	178.95	Softwood, standing under bark, in forest, RER U
		Roundwood timber to be used in PC and M (t)	2.00	10.64	38.47	136.89	Roundwood, softwood, debarked u=70% at forest road
	O	Wood wastes (t)	0.62	3.26	11.81	42.06	Only taken into account in the calculation of WC flow indicator
		Steel nails (kg)	26.94	184.94	836.00	2,800.00	Steel, low-alloyed, at plant RER/S
		Alkyd paint (l)	3.43	0	53.7	136.00	Alkyd paint, white, 60% in solvent, at plant/ RER/S
PC	Subsystem of wood preparation and board shaping						
	I	Roundwood timber (t)	1.50	10.44	38.43	136.89	Roundwood, softwood, debarked u=70% at forest road
	O	Sawn timber (t)	0.83	5.78	21.28	75.81	Sawn timber, softwood, raw, air dried, u= 20%, at plant RER/S
		Wood wastes (t)	0.67	4.66	17.15	61.08	Only taken into account in the calculation of WC flow indicator
	Subsystem of product assembly						
	I	Sawn timber (t)	0.83	5.78	21.28	75.81	Sawn timber, softwood, raw, air dried, u=20%, at plant RER/S
		Steel nails (kg)	14.19	97.61	784.00	2,800.00	Steel, low-alloyed, at plant RER/S
		Alkyd paint (l)	1.37	0	38.08	136.00	Alkyd paint, white, 60% in solvent, at plant/ RER/S
		Light fuel oil (l)	0.57	3.86	50.62	180.81	Light fuel oil, at regional storage/RER/S
		Electricity (kWh)	23.00	157.00	4,032.00	14,400.00	Electricity MV use in E
		Gas (kWh)	56.10	385.90	0	0	Natural gas, at boiler modulating <100 kW/ RER/S
	O	Wood container (t)	0.81	5.52	19.07	67.94	Product
		Wood wastes (t)	0.02	0.26	2.21	7.87	Sent to Final Disposal (FD)
M	Subsystem of wood preparation and board shaping						
	I	Roundwood timber (t)	0.50	0.20	0.04	No[a]	Roundwood, softwood, debarked u=70% at forest road
	O	Sawn timber (t)	0.28	0.11	0.02	No[a]	Sawn timber, softwood, raw, air dried, u=20%, at plant RER/S
		Wood wastes (t)	0.22	0.09	0.02	No[a]	Only taken into account in the calculation of WC flow indicator
	Subsystem of maintenance tasks						
	I	Sawn timber (t)	0.28	0.11	0.02	No[a]	Sawn timber, softwood, raw, air dried, u=20%, at plant RER/S
		Steel nails (kg)	12.75	87.33	52.00	No[a]	Steel, low-alloyed, at plant RER/S
		Alkyd paint (l)	2.06	0	15.62	No[a]	Alkyd paint, white, 60% in solvent, at plant/ RER/S
		Light fuel oil (l)	0	0	51.00	No[a]	Light fuel oil, at regional storage/RER/S
		Electricity (kWh)	38.26	261.98	0	No[a]	Electricity MV use in E
	O	Damaged Sawn timber (t)	0.28	0.11	0.02	No[a]	Sent to final disposal (FD)
		Damaged Steel nails (kg)	12.75	87.33	52.00	No[a]	Sent to final disposal (FD)
FD	I	Wood wastes (t)	0.30	0.37	2.23	7.87	Disposal wood untreated, 20% water, to sanitary landfill/CHU Disposal wood untreated, 20% water, to municipal incineration/CHU Chopper, stationary, electric/RER/U
T	I	Total road transport (t km)	8,305.20	11,350.00	37,987.00	39,945.00	Transport by road, lorry 32 t/RER S

RME Raw materials extraction, *PC* process chain, *M* maintenance, *FD* final disposal, *T* transport, *I* inputs, *O* outputs

[a] The maintenance stage does not exist for the NR spool system.

Table 3 Transport data: distances considered (in km) between the agents

	HR Pallet	LR Pallet	LR Spool	NR Spool
Forest to producer	60	60	56	56
Producer to pool manager centre	290			
Producer to supplier		290	134	134
Producer to trituration	100	100	79	79
Pool manager centre to supplier	50			
Supplier to distributor	210	210	248	248
Supplier to trituration			72	
Distributor to pool manager centre	50			
Distributor to pallet recovery centre		50		
Distributor to trituration				141
Pool manager centre to trituration	290			
Pallet Recovery Centre to landfill		10		
Pallet Recovery Centre to incineration		150		
Pallet Recovery Centre to trituration		100		

in the lower-reuse system. The second highest-impact stage is raw materials extraction, six times higher in the lower-reuse system, which evolves in parallel to impacts of the process chain and final disposal stage. The latter stages are substantially higher in the LR Pallet system, which has a different final disposal scenario. The maintenance stage has a considerable impact in the HR Pallet, but it is 2.6 times lower in the LR Pallet system. The two lowest-impact stages, maintenance and final disposal, contribute all together to less than 30% of the total impact.

Referring to the spool case studies (LR Spool and NR Spool, see Table 6, and Fig. 4), the highest-impact stages are added transport, raw materials extraction and process chain. The impact of transport is nearly the same in both systems (1.1 times higher in NR Spool system), in contrast to the impact of the other two stages, which is 3.6 times higher in the NR Spool system. The final disposal stage shows the same behaviour as raw material extraction. The two lowest-impact stages, maintenance and final disposal, contribute all together to less than 10% of the total impact.

4 Discussion

Higher reuse intensity (see Table 1) has demonstrated a better environmental performance in all categories except for the GWP category, which will be discussed later.

The key factor of this behaviour lies in the amount of materials (mainly wood) needed to satisfy the functional unit due to the higher number of containers required throughout the systems under study, which consequently affects all the system stages. The WC indicator is the only variable that affects the impact of the stages of raw material extraction and process chain because we have considered the same extraction and preparation/shaping/assembly processes in all the case studies. The impact of the following system stages may be conditioned not only by the WC but also by other factors such as the management system, the maintenance index, the final disposal scenario or other processes considered.

As has been shown previously, the impact in the lower-reuse systems (LR Pallet and NR Spool) is higher in all the

Table 4 Cumulative energy demand, WC (flow indicator) and environmental impact (mid-point impact categories) per functional unit

	Units	HR Pallet	LR Pallet	Impact reduction[a] (%)	LR Spool	NR Spool	Impact reduction[a] (%)
EC	GJ	61.61	170.64	63.9	500.66	1,840.51	72.8
WC	T	1.11	5,890	81.0	25.91	92.22	71.9
ARD	kg Sb eq	15.00	24.00	37.5	96.10	219.60	56.2
GWP	kg CO_2 eq	270.00	−5,780.00[b]	–	−19,510.00[b]	−84,440.00[b]	–
ODP	kg CFC-11 eq	0.00033	0.00050	34.0	0.0021	0.0052	59.0
HTP	kg 1,4-DB eq	620.00	1,360.00	54.4	7,500.00	22,230.00	66.3
AP	kg SO_2 eq	12.00	20.00	40.0	96.30	245.80	60.8
EP	kg PO_4^{3-}	2.40	4.80	50.0	12.40	25.00	50.4

[a] This considers the impact reduction derived from higher reuse intensity. Therefore, the GWP impact category has not been considered because it consists of an avoided impact.

[b] The GWP category presents negative values since it corresponds to an avoided impact.

Table 5 Stage contribution to the pallet case-studies global impact per functional unit

	HR Pallet								LR Pallet		
	Units	RME	PC	T	M	FD	RME	PC	T	M	FD
EC	GJ	17.74	0.68	*35.86*	7.09	0.25	*123.54*	4.10	38.56	2.90	1.54
WC	t	1.96	No	No	0.66	No	*13.64*	No	No	0.26	No
ARD	kg Sb eq	0.75	0.27	*13.26*	0.62	0.11	5.16	1.63	*16.32*	0.22	0.65
GWP	kg CO_2 eq	−1,290.00	30.00	*1,870.00*	−410.00	70.00	−9,030.00	200.00	*2,310.00*	−170.00	900.00
ODP	kgCFC-11 eq	0.00001	0.00001	*0.0003*	0.00001	0.00	0.00006	0.00004	*0.00038*	0.00	0.00001
HTP	kg 1,4-DB eq	100.00	10.00	*390.00*	110.00	10.00	*690.00*	70.00	480.00	50.00	80.00
AP	kg SO_2 eq	0.65	0.24	*10.31*	0.70	0.12	4.58	1.42	*12.94*	0.26	0.78
EP	kg PO_4^{3-} Eq	0.12	0.01	*2.16*	0.08	0.02	0.81	0.04	*2.71*	0.03	1.21

The highest impact stages set in italics.
RME Raw materials extraction, *PC* process chain, *T* transport, *M* maintenance, *FD* final disposal

Table 6 Stage contribution to the spool case-studies global impact per functional unit

	Units	LR Spool					NR Spool				
		RME	PC	T	M	FD	RME	PC	T	M	FD
EC	GJ	*351.46*	51.57	88.12	6.67	3.50	*1,492.65*	220.86	112.27	No	14.72
WC	T	*50.23*	No	No	0.05	No	*178.95*	No	No	No	No
ARD	kg Sb eq	24.70	22.10	*45.07*	2.61	1.54	*87.62*	79.06	47.65	No	5.49
GWP	kg CO_2 eq	−28,300.00	2,510.00	*6,270.00*	160.00	180.00	−10,0000.00	*8,940.00*	6,610.00	No	640.00
ODP	kgCFC-11 eq	0.0003	0.00081	*0.00088*	0.00005	0.00009	0.00106	*0.00287*	0.00092	No	0.00032
HTP	kg 1,4-DB eq	*4,220.00*	1,460.00	1,490.00	210.00	140.00	*15,010.00*	5,200.00	1,580.00	No	470.00
AP	kg SO_2 eq	20.80	34.76	*36.88*	1.19	2.70	73.49	*123.64*	38.84	No	9.59
EP	kg PO_4^{3-} Eq	3.79	0.97	*7.43*	0.20	0.06	*13.50*	3.45	7.85	No	0.20

The highest impact stages are set in italics.
RME Raw materials extraction, *PC* process chain, *T* transport, *M* maintenance, *FD* final disposal

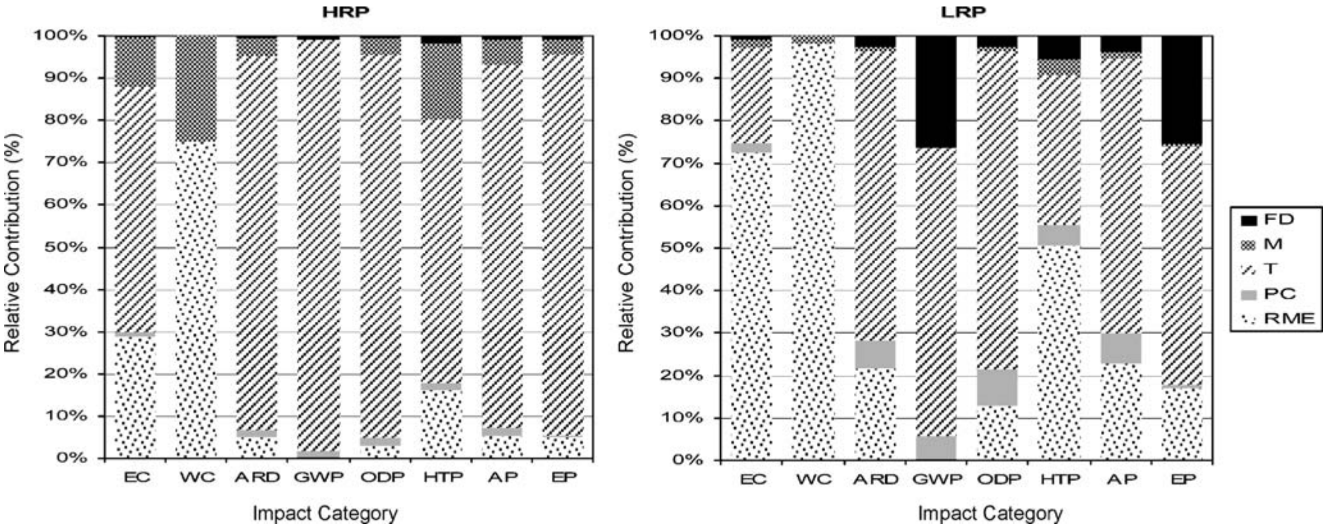

Fig. 3 Relative contribution of each pallet system stage to the impact

stages except for maintenance (see Tables 5 and 6). Superior reuse intensity only implies a slightly higher impact in the maintenance stage, mainly since the maintenance index is low (see Table 1) and also because of the tasks carried out in this stage, which are low demand in terms of materials.

The impact of the transport stage depends not only on the number of containers in circulation—this is to say WC—but also on the number of journeys and the distances involved, taking into account the transport scenarios set out above. Although higher-reuse intensity involves a greater number of journeys and therefore longer distances travelled (see Fig. 2), its added transport impact is compensated for by a lower weight carried because of a lower number of containers within the system. Therefore, as stated before, the impact is only 1.2 and 1.1 times higher in the lower-reuse systems. Consequently, the transport stage does not seem to be a decisive factor explaining the differences in global impact of different reuse intensities.

The final disposal stage impact is conditioned not only by WC but also by the final disposal scenario that is taken into account. In the LR Pallet case study, not only has the recycling scenario been considered—as occurs in HR Pallet, LR Spool and NR Spool—but also incineration (9%) and landfill (6%). As said before, the impacts in the lower-reuse systems are approximately six times those in the higher-reuse systems, mainly due to higher WC. However, this final disposal scenario, in which 15% of the wood is not recycled, specifically increases the EP and GWP impact categories. In this sense, landfill treatment means a 50 times higher EP impact, and incineration implies 12 times higher impact in GWP category for the LR Pallet system.

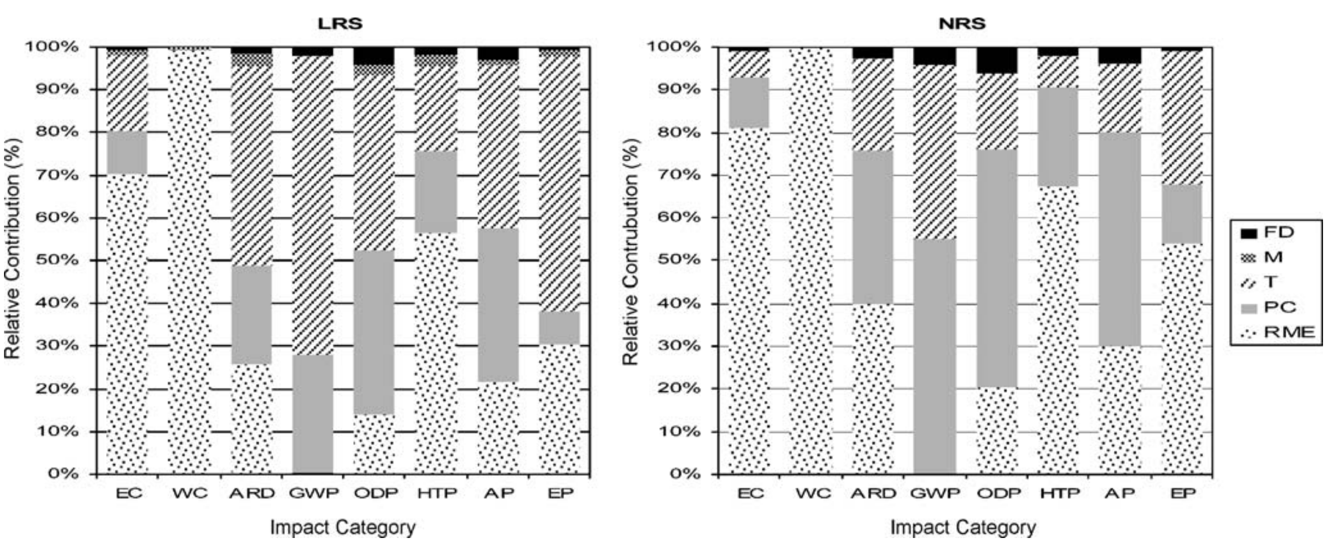

Fig. 4 Relative contribution of each spool system stage to the impact

Wood container systems as a carbon stock The main material consumed in these systems is wood. The consumption of wood in the raw materials extraction and maintenance stages implies a reduction in the GWP impact category, as Gustavson et al. (2006), IPCC (2001), Hillier and Murphy (2000) and Turkendburg et al. (2000) have also stated. However, this avoided impact may be counteracted by the emissions related to the processes involved in each stage. In this sense, the raw material extraction stages have a positive GWP category impact in spite of the emissions of carbon dioxide related to the EC and processes involved in this stage. Considering that, in general, maintenance is low in terms of its requirement of wood, it is possible to observe a negative impact associated to it, as occurs in the LR Spool system (see Table 6). This does not occur in HR Pallet and LR Pallet systems, in which the maintenance tasks involve greater substitution of the pallet pieces (see Table 2).

These results can only be interpreted environmentally favourable when considering wood from sustainable forests. Forestry management for wood-sourcing purposes not only means a movement of carbon and energy displacement from forests to forest products markets (Perez-Garcia et al. 2005) but also has many other additional environmental and social functions such as protective functions in mountainous areas, regulative functions for watersheds, supply of non-wood products, recreation functions and habitat functions for the allocation of environmental burdens related to forestry (Schweinle 2000).

5 Conclusions and recommendations

In general, higher-reuse intensity implies a reduction in the absolute impact in all the flow indicators and impact categories except for GWP when considering containers made of renewable resources such as wood. This decrease is observable in the raw materials extraction, process chain, added transports and final disposal stages at the expense of the maintenance stage. GWP results are better when lower-reuse systems are considered, since higher amounts of wood containers involve bigger carbon dioxide stocks, always considering re-growth of trees in plantations and wood recycling (biomass cascading effect). We expect our results obtained in the GWP category to be interpreted as a demonstration of the environmental benefits of using wooden containers and the need not to prioritise lower-reuse systems because of their better performance in this category, as impacts cannot be reduced at the expense of a greater raw material demand as they are, although renewable, limited.

Maintenance stage is the only one that has a worse environmental performance in the higher reuse systems. An increase of the maintenance index could contribute to a decrease in the impact in the remaining stages, especially RME, process chain and final disposal, thanks to a reduction in the system WC.

The transport stage does not seem to vary in terms of its contribution in absolute values to the global impact, as the distances travelled and the weights transported are thwarted. An improvement in this stage could proportionally reduce the global impact in all the case studies, but it would not mean that reuse is (or not) an environmentally favourable strategy.

As a first approach, the reuse of wooden containers seems to be a strategy capable of reducing the environmental impacts of these systems and to be preferable to the recycling option whilst the package maintenance tasks are still feasible. In this sense, wooden container higher-reuse systems should be encouraged to avoid environment degradation in the ecosystems by means of decreasing container wastes. However, the environmental performance of reuse systems would be improved if we consider recycling as the main final disposal scenario instead of incineration or landfill disposal.

Based on these results, attention should be paid to the maintenance stage, which, being the lowest-impact one, could substantially reduce the impact of the remaining stages.

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